Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 47 (2020) 93–99

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

23rd International Conference on Material Forming (ESAFORM 2020)

Numerical and Experimental Studies of Multi-ply Woven Carbon Fibre Prepreg Forming Process

Connie Qian[a,*], Rachel Weare[a], Corentin Pasco[a], Nadia Kourra[b], Alex Attridge[b], Mark Williams[b], Kenneth Kendall[a]

[a]*Automotive Composites Research Centre, WMG, University of Warwick, Coventry, CV4 7AL, UK*
[b]*Centre for Imaging, Metrology and Additive Technologies, WMG, University of Warwick, Coventry, CV4 7AL, UK*

* Corresponding author. Tel.: +44-247-657-3567. *E-mail address:* connie.qian@warwick.ac.uk

Abstract

Woven carbon fibre prepreg is being increasingly used in high-performance aerospace and automotive applications, primarily because of its superior mechanical properties and formability. A wide range of forming simulation options are available for predicting material deformation during the prepreg forming process, particularly change in fibre orientation. Development of a robust validated simulation model requires comprehensive material characterisation and reliable experimental validation techniques.

This paper presents experimental and numerical methods for studying the fibre orientation in multi-ply woven carbon fibre prepreg forming process, using a double-dome geometry. The numerical study is performed using the commercial forming simulation software PAM-FORM and the material input data are generated from a comprehensive experimental material characterisation. Two experimental validation methods are adopted for fibre shear angle measurement: an optical method for measuring only the surface plies, and a novel CT scan method for measuring both the surface plies and the internal plies. The simulation results are compared against the experimental results in terms of fibre shear angle and the formation of wrinkles to assess the validity of the model.

Keywords: carbon fibre prepreg; forming; process simulation; shear angle; optical method; CT scan

1. Introduction

Woven carbon fibre prepreg is being increasingly used in high-performance applications in both aerospace and automotive industries due to its high specific stiffness and strength. Woven fibre prepreg offers better formability compared to multi-axial non-crimp fabric (NCF) and multi-axial unidirectional (UD) fibre prepreg laminate, as well as the potential of utilising single-stage manufacturing process that cannot be achieved by using dry fabric preform. Like most woven-fabric based materials, the formability of woven fibre prepreg is dominated by intraply shear and interply friction. These deformation mechanisms lead to changes in fibre orientation, and potentially formation of wrinkles in the formed part.

Understanding the material deformation during manufacturing process is the key to improving quality, and to predict the structural performance of the part following manufacturing. Process simulation has been widely adopted as a design tool for predicting the change in fibre orientation and the formation of wrinkles in composites sheet forming processes. There are two main types of forming simulation models for woven-fibre based materials: kinematic models and finite element (FE) models. Kinematic models [1] simulate the deformation of material by mapping a flat layer of mesh onto a target surface. The results predicted by kinematic models generally have limited accuracy because the influence of the

10.1016/j.promfg.2020.04.142

material properties and the process conditions are not included. FE models are typically developed using either generic FE packages (e.g. ABAQUS) [2-4] or dedicated process simulation software with an integrated FE solver (e.g. PAM-FORM) [4, 5]. Such models require extensive characterisation of the material and the contact properties. While it has been demonstrated in [4] that both generic FE packages and dedicated process simulation software could provide accurate predictions in terms of fibre orientation and formation of wrinkles, specific user-material subroutines have to be developed for generic FE packages, which makes them less desirable for commercial applications.

Quantifying the predictive validity of a model for a forming simulation using data collected from the experimental forming process is necessary for determining the quality of the model. Most previous researchers have adopted Grid Strain Analysis (GSA) [6] method for experimentally measuring shear angle and fibre orientation in fabric forming process. GSA relies on a grid system constructed (usually printed) on the material surface, so that the shear angle can be calculated by comparing the deformed grid against the undeformed grid, and the fibre orientation can be subsequently determined from the shear angle. The implementation of GSA in multi-ply, multi-axial prepreg forming process is challenging because once moulded, the plies can no longer be separated for individual inspection. A comprehensive review of experimental methods for post-moulding inspection of fibre orientation in multi-ply, multi-axial carbon fibre composite part using state-of-art inspection techniques was provided in [7], where comparisons were made between optical method, eddy current and CT scan. It has been demonstrated in [7] that all three methods only provide limited information: the optical method only measures the surface plies; the eddy current method cannot distinguish plies with same fibre angle; and the CT scan method has failed to determine fibre orientation due to the limited resolution and the low contrast between carbon fibre and matrix. The use of tracer fibre has also been investigated in the literature to facilitate the inspection of fibre orientation. A study conducted in [8] attempted to use CT scan to study the squeeze flow behaviour in thermoplastic woven fibre prepreg laminates by placing copper wires at the ply/ply interface. Although the wires were clearly visible in the CT scan, this method did not provide reliable information about the fibre orientation as the wires at the interface would not follow the deformation of the fabric. Thermal imaging technique was adopted in [9] to inspect fibre orientation in glass fibre composites, where steel tracer wires were interwoven into the material to create a grid pattern prior to forming. Although this method provides means of accurate measurement of fibre orientation using GSA, full-field assessment of 3D part requires measurements to be stitched together as thermal imaging does not 'see-through' the part, which could compromise the accuracy of the measurement.

This paper seeks robust and reliable experimental methods for measuring shear angle in multi-ply woven carbon fibre composites, and demonstrates how the experimental data can be used to validate forming simulation models. A double-dome geometry has been chosen as the demonstrator geometry and a Double Diaphragm Stamp Forming (DDSF) process is used to form and mould the selected woven carbon prepreg. The numerical model is developed using ESI's commercial software PAM-FORM, and supported with comprehensive material characterisation. Two experimental shear angle measurement methods are investigated in this work: an optical method which measures the shear angle at the surface plies, and a novel CT scan method utilising copper tracer wires which measures the shear angle at both surface and internal plies.

2. Experimental approach

2.1. Forming of multi-ply woven carbon fibre prepreg

A double-dome geometry with a uniform 1.9 mm thickness was chosen as the demonstrator geometry and manufactured using a DDSF process. All double domes manufactured in this work contained four plies of the same woven prepreg with a symmetrical, quasi-isotropic layup sequence $[(0°/90°)/\pm45°]_s$ (see Fig. 1). The plies were labelled from the bottom (male mould/punch side) to the top (female mould/die side) as 1st ply to 4th ply. During the DDSF process, flat prepreg laminate was positioned between two stretchable diaphragms clamped and sealed around the perimeter (see Fig. 1). A vacuum was applied between the diaphragms, and maintained throughout the process. Prior to forming, the DDSF assembly was shuttled into an infrared oven and the laminate heated to approximately 80°C, a temperature well below that of the cure onset of epoxy resin system, yet sufficiently high to lower the viscosity of the resin. The DDSF assembly was subsequently shuttled into the press, stamp formed and cured using a matched metal mould.

The woven prepreg used in this work was a 2x2 twill weave carbon/epoxy prepreg, with 12k tow-size, 667 gsm areal weight and 52% Vf. The material is commercially available, and is specifically designed for compression moulding and high-volume, automotive applications. Typical curing time is 5 minutes at 140°C but can be adjusted depending on the moulding temperature. The diaphragm was an Ethylene tetrafluoroethylene release film with 50 μm thickness, 350% maximum elongation and 260°C maximum operating temperature. For reasons of confidentiality, further details about the DDSF process and the materials used in this work will not be disclosed in this paper.

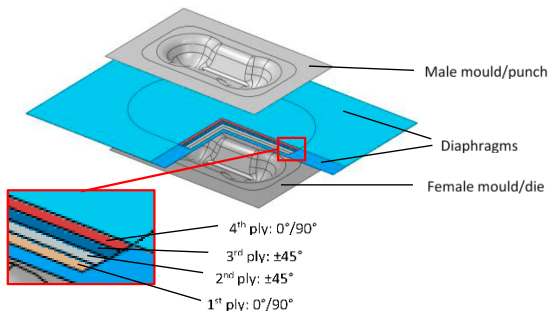

Fig. 1 Schematic of the DDSF assembly

2.2. Optical method for shear angle measurement

The photogrammetry system, Argus® GOM was used as an optical method to measure the shear angle at the surface plies.

The experimental setup is shown in Fig. 2. One quarter ofthe double dome was selected as the region of interest (ROI) where white dots were applied onto the double-dome surface at yarn crossovers using a paint pen. The ROI was then coated with an anti-reflection spray to mitigate the glare that would impede the measurement process. A series of images were taken for the ROI from different angles using a CCD camera, with a set of targets placed around the ROI. The position of the camera for each image was calculated by GOM using the targets as references. Automatic GSA was performed in GOM by correlating the painted dotted pattern to a prescribed grid with a uniform spacing of 4mm (the distance between the centres of two adjacent crossovers on the undeformed prepreg) and full-field mapping of the shear angle was generated.

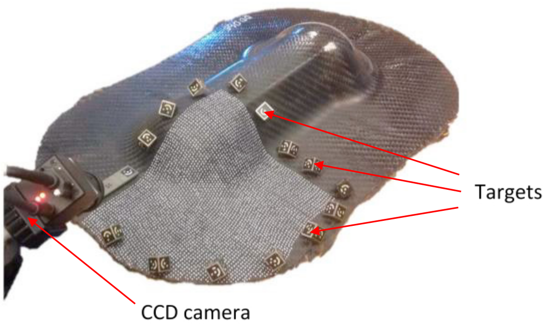

Fig. 2 Experimental setup for photogrammetry analysis of shear angle using GOM.

2.3. CT scan for shear angle measurement

A novel CT scan method was developed to facilitate shear angle measurement at both surface and internal plies, where a copper tracer wire grid similar to the one in [9] was used: 0.2 copper wires were spaced at 3-tow intervals along each fibre direction, threaded through tow intersection points by hand at 3-tow intervals (Fig. 3). This approach utilises the large contrast in density between the copper and the composites, allowing fibre orientation to be inspected at macro-scale. It also eliminates the need to stitch measurements as with thermal imaging method in [9], because the X-ray used in CT scan can penetrate through the material, allowing 3D parts to be inspected in a single scan. Two double domes were manufactured for CT scans: one with copper wires along the 0° direction in the 1st ply and the 90° direction in the 4th ply, and the other one with copper wires along the 45° direction in the 2nd and the -45° direction in the 3rd ply. Only one quarter of each double dome was interwoven with copper wires and CT scanned due to the symmetry (Fig. 3b). CT scans were performed on a Nikon X-Tek XT H 225/320 LC scanner and the settings utilised for this study are provided in Table 1. 3D model of the deformed copper wire grid was reconstructed from the CT scan using Scout-and-Scan Control System software. It should be noted that in this approach, because the orthogonal copper wires were in different plies, they only indicated the fibre orientation in the ply containing copper wires. Nevertheless, the shear angle could be calculated using GSA by assuming the shear angle was the same for plies with same orientation.

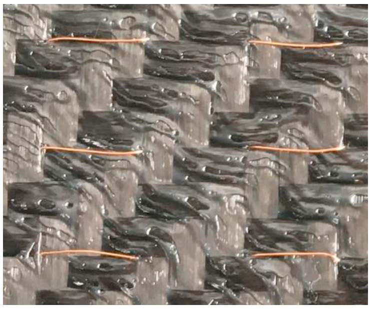

Fig. 3 Closed-up view of the woven carbon prepreg interwoven with copper tracer wires.

Table 1. CT scan settings and information about the scan

CT scanning settings	
Exposure Voltage	200kV
Exposure Power	13W
Exposure Time	3sec
Gain	24
Information about the scan	
Voxel size	128.5μm
No of Projections	3142

2.4. Prepreg intraply shear tests

The intraply shear behaviour of the prepreg material was characterised using a picture-frame test fixture described in [10], where a novel discrete point tracking method was used to provide simple and accurate shear angle measurements during the test. The arm length of the picture frame was 180mm and the edge length of the effective shear zone was 100mm. The test was conducted isothermally at 80°C inside a thermal chamber. Various crosshead speeds were used (1 mm/s, 5 mm/s and 8.33 mm/s) to study the strain-rate effects on the intraply shear behaviour. Experimental shear force vs. shear relationship at different crosshead speeds are presented inFig. 4. According to Fig. 4, the material experiences nonlinear shear behaviour, and at any given shear angle, the shear force increases with increasing crosshead speed. For all three crosshead speeds, the shear force increases dramatically once the shear angle reaches approximately 30°, which indicates the onset of shear locking.

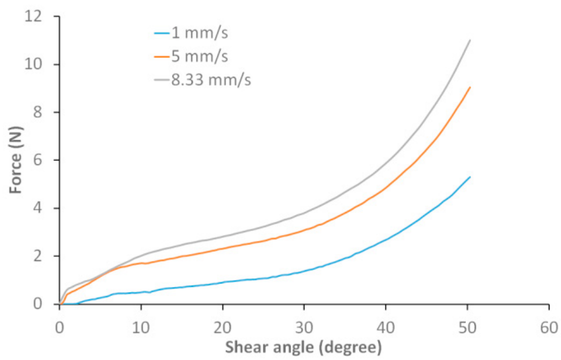

Fig. 4 Experimental force vs. shear angle curves for the picture frame test at various crosshead speeds. The arm length of the picture frame was 180mm and the edge length of the effective shear zone was 100mm.

2.5. Friction tests

A friction test rig with a heating rate of up to 80°C/min has been specifically designed by the co-authors in [11] to facilitate the characterisation of fast-curing prepreg materials. A number of contact interfaces existed in the DDSF process, including the interply (ply/ply) interface, ply/diaphragm interface and mould/diaphragm interface. Table 2 summarises the test parameters for all friction tests performed in this study and the experimental coefficient of friction (CoF) value for each interface. For interply friction, tests were performed under an applied normal pressure of 1 bar and 2 bar, and at 1mm/s and 5mm/s relative speed between the plies. Both the 0/0 interface and 0/45° interface were tested to study the influence of ply orientation. Friction tests at the ply/diaphragm interface and mould/diaphragm interface were performed under 1 bar normal pressure and at 1mm/s relative speed. Material orientation effects were not considered at the ply/diaphragm interface nor at the mould/diaphragm interface. Three repeats were performed for each combination of test conditions, and the coefficient of variation (CoV) was also presented in Table 2.

Table 2. Coefficient of friction (CoF) obtained from the friction tests

Interface	Relative speed (mm/s)	Test pressure (bar)	CoF	CoV (%)
Interply 0/0	1	1	0.1432	13.1
	1	2	0.1297	2.4
	5	1	0.2282	8.3
	5	2	0.2063	19.6
Interply 0/45°	1	1	0.1024	1.2
	1	2	0.0713	11.8
	5	1	0.2194	7.1
	5	2	0.1136	13.4
Ply/diaphragm	1	1	0.21	6.7
Mould/diaphragm	1	1	0.46	9.3

2.6. Diaphragm tensile tests

Straight sided tensile diaphragm specimens of 100mm and 25mm were cut in both longitudinal and transverse directions using a CNC fabric cutting table. Tensile tests were performed in accordance to BS EN ISO 527-3:1996 on an Intron 5985 Universal Test Machine with 500kN load cell and thermal chamber. All specimens were tested at 80°C to be representative of forming temperatures. Constant head displacement rate of 1mm/s and 8.33mm/s were used for longitudinal specimens and only 8.33mm/s was used for transverse specimens. Instron Advanced Video Extensometry was used for optical strain measurement using a 25mm gauge length and 20mm gauge width. Typical experimental stress-strain curves for the diaphragm material is presented in Fig. 5. According to Fig. 5, the tensile behaviour of the diaphragm material can be considered isotropic and strain-rate insensitive, with 6.3% difference in the ultimate tensile strength and 25.7% difference in the elongation at break between the longitudinal and the transverse specimens, and 14.1% difference in the ultimate tensile strength and 13.5% difference in the elongation at break between specimens tested at 1 mm/s and specimens tested at 8.33 mm/s.

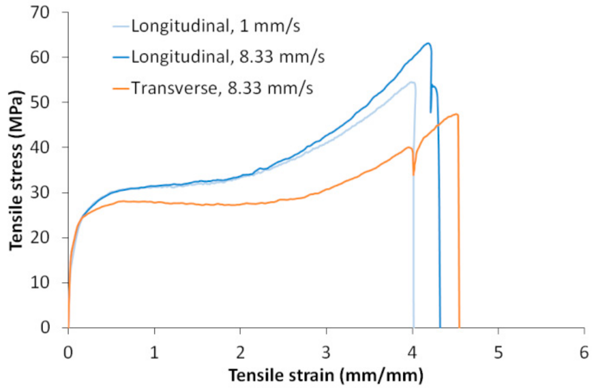

Fig. 5 Typical experimental tensile stress-strain curves for the diaphragm material.

3. Numerical simulation approach

The DDSF simulation was performed using ESI PAM-FORM, solver v2018. The male and female moulds were modelled as rigid bodies and meshed in Atair Hypermesh using triangular shell elements with a global seed size of 5mm. The diaphragms and the plies were meshed with PAM-FORM's built-in blank editor using mixed quadrilateral and triangular shell elements with a global seed size of 5mm. The mesh for each ply was generated along the fibre direction to avoid unrealistic shear locking of the elements and to improve the accuracy of the analysis.

Material input parameters used in the process simulation are summarised in Table 3. The density and the tensile stiffness of the prepreg material and the diaphragm material were provided by the material manufacturers. For the intraply shear behaviour for prepreg material and the tensile behaviour for diaphragm material, PAM-FORM supports direct input of tabulated experimental data as a function of test rate. Therefore, the shear force-shear angle data presented in Fig. 4 and the tensile stress-strain data presented in Fig. 5 were directly used in the process simulation.

The penalty contact algorithm was used at all interfaces using default contact stiffness, with the corresponding CoF obtained from the friction tests in Table 2. Default contact thickness (half of the total thickness of two plies) was used at all ply-ply interfaces. Due to the small thickness of the diaphragms, using the default contact thickness at diaphragm-diaphragm interface and diaphragm-mould interfaces led to stability issues. Therefore, contact thickness was artificially increased to 0.25mm at these interfaces, and the cavity height was increased by 0.4mm to compensate for the added thickness.

The DDSF process was modelled in three stages in accordance with the experimental procedure. In the first stage, all degree of freedoms were constrained for the diaphragm edges, and pressures of 1 bar were applied to the upper surface of the top diaphragm and the bottom surface of the bottom diaphragm for 10 seconds. The same boundary conditions and pressures were applied for the remaining stages. In the second stage, the male mould moved downwards at 5 m/s until the edge was levelled with the edge of the top diaphragm and the plies and diaphragms were draped over the male mould. In the last stage the female mould moved upwards at 5 m/s to close the cavity and complete the forming. A velocity scale factor of 0.01 was used in all steps to compensate the influence of artificially increased tool velocity.

Table 3. Summary of the material input parameters used in the process simulation. E denotes the tensile stiffness and ν denotes the Poisson ratio.

Prepreg material	
Density	1516 kg/m^3
Fibre Vf	52%
E_1, E_2	60GPa
Diaphragm material	
Density	1720 kg/m^3
E	1GPa
ν	0.45

4. Results and discussions

4.1. Model validation using optical method

Fig. 6 compares the shear angle distribution at the 1st (0/90°) ply between the experimental results and the simulation results. Good agreement has been achieved for both the contour and the magnitude of the shear angle distribution between the experimental results and the prediction. For both plots, large shear angle (maximum 43.7°) is observed in the transition area between the dome section and the flat section, and at 45° from the longitudinal axis of the part. This large shear angle is possibly due to the high local surface curvature, as well as the large frictional force between the 0/90° ply and the ±45° ply underneath. This observation also agrees with the results reported in [3] where dry glass fibre fabric with same quasi-isotropic layup arrangement was studied. It can be seen from Fig. 6 that the experimental plot contains missing data. One possible reason for the missing data is that due to the large deformation in this case, is it difficult for GOM to construct a coherent grid connecting every dot from the chosen camera position. Nevertheless, the region with larger shear angles is considered more critical in terms of model validation, and the regions with missing data generally have very small shear angles as suggested by the simulation.

4.2. Model validation using CT scan

The CT scan for the double dome with copper wires in the 0/90° plies (1st and 4th) is presented in Fig. 7 and compared with the deformed mesh for the 1st ply predicted by the simulation. Fig. 7(a) shows that a clear reconstruction of the copper wire network can be achieved using the CT scan technique described in Section 2.3. The copper wires show various levels of waviness across the ply in Fig. 7 because they were only constrained in-plane at the points where they were threaded through the prepreg. As a result, the unconstrained segments of the wires could experience in-plane deformation due to intraply friction, resin flow and other forces arising during forming. Shear angles were measured from the CT scan in regions with low waviness level as illustrated in Fig. 7 (a): the angle between intersecting warp/weft yarns, α was firstly measured by drawing two straight lines connecting the two intersecting points along the warp and weft directions, and the shear angle was equal to 90°-α. In Fig. 7 (b) shear angle was obtained as direct output from PAM-FORM. Good agreement was achieved between the experimental shear angles and the simulation results at the four selected locations in Fig. 7, with less than 14.1% difference. It is worth noting that according to Fig. 7 (a), large shear angles occurred in the same region as in the 1st ply (see Fig. 6).

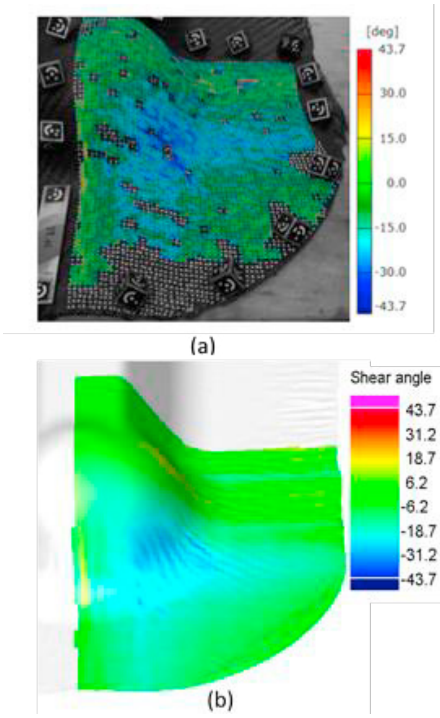

Fig. 6 Comparison of shear angle within the 1st ply (0/90°): (a) experimental result and (b) simulation result.

The CT scan for the double dome with copper wires in the ±45° plies (2nd and 3rd) is presented in Fig. 8 and compared with the deformed mesh for the 2nd ply predicted by the simulation. Unlike the previous observations from the 0/90° plies, higher shear angles were observed in the transition region between the dome section and the flat section, but along the longitudinal axis of the part. Furthermore, a single wrinkle was observed from both the CT scan and the simulation, at approximately 45° from the longitudinal axis of the double dome. It is worth noting that due to the large size of the wrinkle, the local fibre volume fraction in that location is higher, and a dry area was observed at the same location in the 1st and 4th plies, clearly identified from the surface of the part (see Fig. 8 (c)). Shear angles were measured at three different locations as shown in Fig. 8 using the same method as in the previous paragraph. Again, good agreement was achieved between the experimental shear angles and the simulation results with less than 19.7% difference.

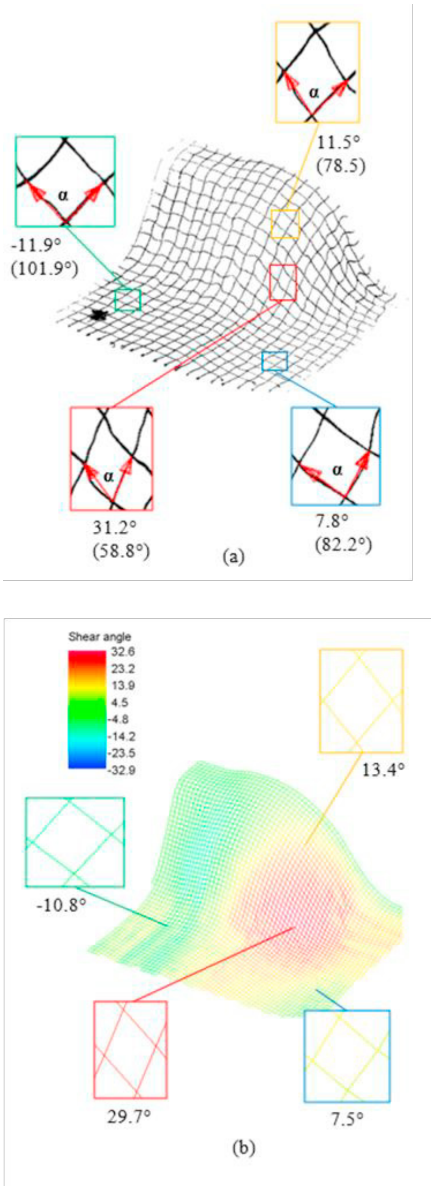

Fig. 7 Double dome with copper wires in the 1st and 4th ply (0/90°): (a) CT scan and (b) simulation. The numbers under the boxes indicate the shear angle values and the values in bracket are the values of α.

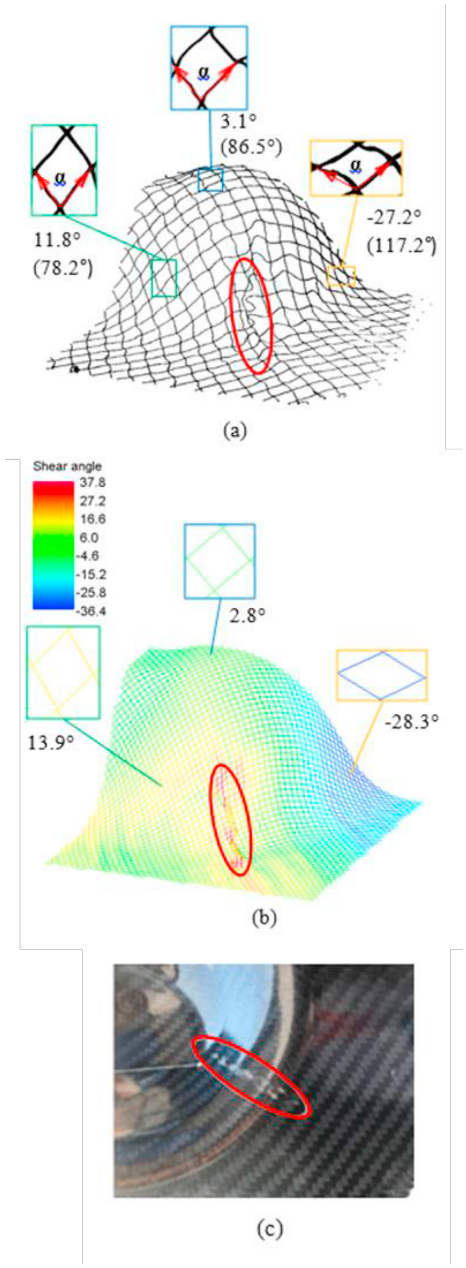

Fig. 8 Double dome with copper wires in the 2nd and 3th ply (±45°): (a) CT scan, (b) simulation and (c) wrinkle visible from the 4th ply. The numbers under the boxes indicate the shear angle values and the values in bracket are the values of α.

Future development of the proposed CT scan method will focus on developing a GSA program to calculate automatically the shear angle at each grid intersection point and to generate a full-field shear angle mapping using an interpolation approach. The accuracy of the shear angle measurement can be improved by interweaving the copper wire grid within the same ply. Reducing the interval of the stitches may also improve the quality of measurement by reducing the level of waviness of the copper wires, which can be easily achieved using an automated stitching facility.

5. Conclusions

A forming simulation for woven carbon fibre prepreg was developed in PAM-FORM and comprehensive material characterisation was carried out to provide the input data for the model. Novel experimental shear angle measurement methods using state-of-art inspection techniques were investigated. The optical method provided automated measurement by using the embedded photogrammetry software, but only surface plies could be measured. The CT scan method combined with the use of copper tracer wires was demonstrated to be a robust method of measuring both internal and surface plies, but further development is required to achieve automated shear angle measurement and to improve the reliability of the measurements.

The shear angle predicted by the simulation showed good agreement with the experimental data obtained using both methods. The simulation also successfully predicted the formation of wrinkles on the internal plies, which was captured by the CT scan method.

Acknowledgements

The work presented in this paper was completed as part of the “Integrated compression moulding process” (InterCOMP) project. The authors gratefully acknowledge the financial support of Innovate UK (Project Reference 102635).

References

[1] Mack C, Taylor HM. 39—The Fitting of Woven Cloth to Surfaces. Journal of the Textile Institute Transactions 1956;47(9):477-488.
[2] McGuinness GB, ÓBrádaigh CM. Development of rheological models for forming flows and picture-frame shear testing of fabric reinforced thermoplastic sheets. Journal of Non-Newtonian Fluid Mechanics 1997;73(1):1-28.
[3] Khan MA. Numerical and Experimental Forming Analyses of Textile Composite Reinforcements Based on a Hypoelastic Behaviour. 2009.
[4] Dörr D, Brymerski W, Ropers S, Leutz D, Joppich T, Kärger L, Henning F. A Benchmark Study of Finite Element Codes for Forming Simulation of Thermoplastic UD-Tapes. Procedia CIRP 2017;66:101-106.
[5] Sutcliffe MPF, Sharma S, Long AC, Clifford MJ, Gil RG, Harrison PG, Rudd CD. A Comparison of Simulation Approaches for Forming of Textile Composites. *The 5th International ESAFORM Conference on Materials Forming*. Krakow, Poland; 2002.
[6] Martin TA, Christie GR, Bhattacharyya D. Chapter 6 Grid strain analysis and its application in composite sheet forming. In: Bhattacharyya D, editor Composite Materials Series. Elsevier; 1997, p. 217-245.
[7] Schug A, Kapphan G, Bardl G, Hinterhoelzl R, Drechsler K. Comparison of Validation Methods for Forming Simulations. 2018.
[8] Sorba G, Binetruy C, Leygue A, Gudiwada S, Lebrun J-M, Bertrand F, Comas-Cardona S, Jollivet T. Squeeze flow in heterogeneous discontinuous viscous woven prepreg laminates : experimental measurements and 3D modeling. Revue des composites et des matériaux avancés 2017.
[9] Nino GF, Bergsma O, Bersee H, Beukers A. Influence of fiber orientation on mechanical performance for thermoformed composites. ICCM International Conferences on Composite Materials 2007.
[10] Pasco C, Khan M, Kendall K. A novel discrete method of shear angle measurement for in-plane shear properties of thermoset prepreg using a point-tracking algorithm. Journal of Composite Materials 2019;53(14):2001-2013.
[11] Pasco C, Khan M, Gupta J, Kendall K. Experimental investigation on interply friction properties of thermoset prepreg systems. Journal of Composite Materials 2019;53(2):227-243.